NAVAL AIR WARFARE CENTER AIRCRAFT DIVISION
PATUXENT RIVER, MARYLAND

NAWC Aircraft Division NAVAL AIR WARFARE CENTER

UNITED STATES NAVY

TECHNICAL REPORT

REPORT NO: NAWCADPAX--98-236-TR

AIRCRAFT DEPAINTING TECHNOLOGY

by

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18 March 1999

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NAVAL AIR WARFARE CENTER AIRCRAFT DIVISION
PATUXENT RIVER, MARYLAND

NAWCADPAX--98-236-TR
18 March 1999

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REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY (Leave Blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	18 March 1999	Technical Report

4. TITLE AND SUBTITLE

Aircraft Depainting Technology

5. FUNDING NUMBERS

6. AUTHOR(S)

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7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(ES)

Naval Air Warfare Center Aircraft Division
22347 Cedar Point Road Unit #6
Patuxent River, Maryland 20670-1161

8. PERFORMING ORGANIZATION REPORT NUMBER

NAWCADPAX--98-236-TR

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Naval Air Systems Command
47123 Buse Road Unit #IPT
Patuxent River, Maryland 20670-1547

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

Chemical paint strippers historically used for aircraft contained toxic and hazardous components; aircraft depainting operations are a major source of hazardous waste generation in DOD. Federal and state agencies have begun to restrict using these hazardous materials and Government directives require significant reductions in hazardous waste generation. The Naval Air Systems Team has partnered with the Air Force at WR-ALC in investigating mature, advanced paint removal technologies and has taken a multiprocess approach to meeting the requirements of aircraft and component stripping at various levels of maintenance. Under this program, the Navy pursued development of non-HAP chemical paint strippers as alternatives for methylene chloride based strippers. In addition, the Navy has selected the xenon flashlamp/CO_2 (Flashjet®) process for materials testing and developed a prototype semiautomatic manipulator system incorporating the Flashjet® process for depainting large aircraft. As a result of extensive materials testing, NAVAIRSYSCOM authorized using the Flashjet® paint removal process on metallic fixed-wing aircraft surfaces. The approval process for using Flashjet® on fixed-wing organic composite aircraft surfaces is nearly complete. Relative life cycle costs per square foot of comparable aircraft surface were found to be favorable for Flashjet® paint removal compared to methylene chloride chemical stripping or plastic media blasting.

14. SUBJECT TERMS

Depainting
Paint Strippers
Non-HAP
Flashjet®

15. NUMBER OF PAGES

38

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAR

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102

SUMMARY

Chemical paint strippers historically used for aircraft have contained toxic and hazardous components, and the aircraft depainting operations are a major source of hazardous waste generation in DOD. Federal and state agencies have begun to restrict the use of these hazardous materials and Government directives require significant reductions in hazardous waste generation. The Naval Air Systems Team (Laboratories, Depots, and Headquarters) has partnered with the Air Force at Warner Robins Air Logistics Center in investigating mature, advanced paint removal technologies and has taken a multiprocess approach to meeting the requirements of aircraft and component stripping at various levels of maintenance. Under this program, the Navy pursued development of nonhazardous air pollutant chemical paint strippers as alternatives for methylene chloride based strippers. In addition, the Navy has selected the xenon flashlamp/carbon dioxide (Flashjet®) process for materials testing and developed a prototype semiautomatic manipulator system incorporating the Flashjet® process for depainting large aircraft. As a result of extensive materials testing, NAVAIRSYSCOM authorized use of the Flashjet® paint removal process on metallic fixed-wing aircraft surfaces. The approval process for use of Flashjet® on fixed-wing organic composite aircraft surfaces is nearly complete. Relative life cycle costs per square foot of comparable aircraft surface were found to be favorable for Flashjet® paint removal compared to methylene chloride chemical stripping or plastic media blasting.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the support of the Strategic Environmental Research and Development Program and the Office of Chief of Naval Operations Environmental Protection, Safety and Occupational Health Division (CNO N45) in sponsoring the Navy's Aviation Pollution Prevention Technology Program. The authors also wish to thank the Warner Robins Air Logistics Center Technology Insertion Office (WR-ALC/TIEDM) and the NAVAIRSYSCOM Facilities and Environmental Programs Office (AIR-8.0Y) for their cooperation and support.

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INTRODUCTION

GENERAL

During the life cycle of military aircraft, paint stripping and recoating are required periodically for inspection, maintenance, and repair as well as for changes in paint schemes and special-purpose coatings. Over 1,000 rotary- and fixed-wing aircraft are stripped in DOD Depots each year. Commercial aircraft may similarly require stripping and repainting approximately every 3 to 7 years during their operating lifetimes. In the past, aircraft painted surfaces consisted primarily of aluminum alloys. Currently, military and commercial aircraft surfaces are increasingly comprised of reinforced organic matrix composites, with different damage susceptibilities. The paint systems used on military aircraft over the last 25 years have included epoxy primers and polyurethane topcoats, which are more difficult to remove than the enamels and acrylics used earlier.

Historically, the chemical paint strippers used on aircraft surfaces have been formulated with methylene chloride, which penetrates and attacks polymeric coatings quickly and effectively. To enhance the stripping of tough epoxy and polyurethane coatings, phenol activators were added. Chemical stripping is labor-intensive and time-consuming and frequently requires additional sanding and scraping followed by extensive rinsing. Paint removal operations at the NADEP's are one of DOD's greatest sources of hazardous waste, requiring increasingly expensive treatment and disposal procedures. Methylene chloride is a toxic organic compound that increases the total toxic organic level in maintenance activity waste streams. The elimination of chemical stripping of aircraft with methylene chloride and phenols is aimed at meeting the goals of the Clean Air and Clean Water Acts, the Resource Conservation and Recovery Act (RCRA), and the National Emission Standards for Hazardous Air Pollutants (NESHAP).

This program was undertaken to investigate alternative methods for aircraft paint removal in order to comply with federal and state regulations while maintaining operational readiness and aircraft performance. The objective was to develop environmentally safe and effective replacements for hazardous chemical paint stripping for use on Navy aircraft.

BACKGROUND

As the environmental movement gained strength in this country, the Navy and industry began to investigate alternative methods of paint removal applicable to aircraft. The Navy approved plastic media blasting (PMB) for metallic substrates in 1991[1] and for composite laminate substrates in 1994[2], giving the NADEP's an acceptable mechanical method to remove paint from aircraft surfaces. Investigations and testing were begun to identify acceptable chemical paint removers that would meet proposed OSHA limits on methylene chloride. In the meantime, the Environmental Protection Agency (EPA) began developing the NESHAP standards, which became the drivers to develop nonhazardous air pollutants (non-HAP's) paint strippers. In addition, alternate nonchemical coating removal technologies were being developed.

Continued work on non-HAP's paint removers is yielding results. A non-HAP's Federal Specification has been written and issued: "Remover, Paint, No Hazardous Air Pollutants (HAP's)" (TT-R-2918). Manufacturers of non-HAP's paint removers are developing and beginning to qualify second generation non-HAP's strippers. Critical qualification tests (i.e., hydrogen embrittlement) are being refined to provide accurate, quantifiable data in order to assess performance and potential damage.

Flashlamp, carbon dioxide (CO_2) pellet blasting, high-pressure water, sodium bicarbonate blasting, and medium-pressure water (MPW) were all emerging technologies for future paint removal. Under this program, the Navy chose a combination of flashlamp/CO_2 blasting (Flashjet®) developed by Boeing St. Louis as the most promising for environmental safety and efficiency for minimizing hazardous waste. A flashlamp/CO_2 mobile system, applicable to large aircraft, was demonstrated at NADEP Jacksonville in June 1998.

REGULATORY COMPLIANCE ISSUES

PAINT STRIPPING – ENVIRONMENTAL DRIVERS

PAINT STRIPPER CHEMICALS

Chemical paint strippers for aircraft exteriors are aggressive liquid products designed to break primary and secondary chemical bonds within the coating polymer and between the coating and substrate and to swell the coating polymer, causing it to blister away from the substrate. Alkaline paint strippers include reactive components such as phenol, ammonia, monoethanolamine, and various other amines. Acidic strippers include strong organic acids as reactive components, such as formic acid and hydroxyacetic acid. Both types make use of methylene chloride as the swelling agent that penetrates and carries the reactants into the coating. Other solvents can be used for viscosity control (methanol), to modify solvency (methyl ethyl ketone), and as a solvent for paraffin wax evaporation retarder (toluene). In addition, sodium chromate is used to inhibit the corrosion of substrates during the stripping process.

POLLUTION REGULATIONS

These aggressive chemicals also display their reactivity in the environment and within living organisms. Workplace regulations developed by the National Institute of Occupational Safety and Health and American Conference of Government and Industrial Hygienists (ACGIH)[3] severely restrict the chemical exposure of personnel to the types of hazardous materials listed in table 1.

Table 1
TYPES OF HAZARDOUS MATERIALS

Chemical	OSHA Permissible Exposure Limit(1) (ppm)	ACGIH Threshold Limit Value(1) (ppm)
Methylene Chloride	25	50(2)
Phenol	5	5
Ammonia	50	25
Monoethanolamine	3	3
Formic Acid	5	5
Hydroxyacetic Acid	N/A	N/A
Methanol	200	200
Methyl Ethyl Ketone	200	200
Toluene	200	50
Chromium VI Compounds (water soluble)	0.1 mg/m^3	0.05 mg/m^3(3)

NOTES: (1) Time weighted average for an 8-hr day.
(2) A1 – Classified as an animal carcinogen.
(3) A3 – Classified as a confirmed human carcinogen.

The National Toxicology Program lists chromium VI compounds as known carcinogens.

In addition to workplace requirements, effective 30 September 1998, emission of stripper components into the atmosphere will be regulated by the Aerospace NESHAP. This NESHAP will restrict the emissions to no more than 365 lb of HAP's per military aircraft[4]. This equates to 50 gal of 35% methylene chloride paint stripper.

The EPA has classified methylene chloride and phenol as HAP's. The standard for depainting operations at major source facilities specifies that no HAP's shall be emitted from chemical depainting operations with an exception for radomes, parts normally removed from the aircraft during depainting and for spot stripping or decal removal. Facilities that choose to use mechanical means for depainting are subject to operating requirements for depainting operations generating airborne inorganic HAP's, including closely monitored control with particulate filters or waterwash systems. Removal of paint by sanding is exempt. HAP's include chromium compounds, methylene chloride, methanol, methyl ethyl ketone, phenol, and toluene. Local regulatory districts (for example, the city of Jacksonville, Florida) have limited the use of methylene chloride based strippers in an effort to encourage the development of alternative technology.

Finally, disposal of chemical stripper waste is regulated under the RCRA, which lists methylene chloride, phenol, formic acid, methyl ethyl ketone, toluene, and chromium compounds as hazardous waste. Effluent from locally operated treatment works must meet the strict requirements of the National Pollutant Discharge Effluent Standards established for each watershed region of each state.

In summary, the storage, handling, use, disposal, and cleanup of methylene chloride based chemical paint stripping is heavily regulated and is not environmentally friendly.

Executive Order 12856, signed by President Clinton in August 1993, requires federal agencies to drastically reduce waste generation. Specifically, federal facilities are required to reduce their releases and off-site transfers of more than 300 toxic chemicals by 50% by 31 December 1999, using 1994 Toxic Release Inventory (TRI) figures as a baseline. The 1994 data for 127 DOD facilities showed total releases and off-site transfers of 17 million pounds of TRI chemicals. Approximately 30% of 1994 DOD bulk releases were directly attributable to methylene chloride alone, primarily from paint stripping operations.

INVESTIGATIONS OF ALTERNATIVE PAINT REMOVAL METHODS NONHAZARDOUS AIR POLLUTANT CHEMICAL STRIPPERS

Early alternative candidates for methylene chloride based paint strippers included acid or alkaline-activated benzyl alcohol based removers and N-methyl pyrrolidone (NMP) based removers. Of the three, the alkaline-activated benzyl alcohol products have demonstrated the greatest potential for general use on naval aircraft. Acid-activated removers have limited application due to their corrosive effect on magnesium and the potential for embrittlement of high-strength steel components such as landing gear, tail hooks, fasteners, and wing attachment bolts. NMP paint removers are most effective at elevated temperatures (160°F to 180°F), and thus more suitable to tank stripping operations.

In late 1992, the NAWCAD Patuxent River Materials Laboratory evaluated two benzyl alcohol based products, acid-activated and alkaline-activated. Although the acid-activated material stripped laboratory panels in less than 1 hr, the product proved corrosive to magnesium and embrittling to high-strength steel, as anticipated. In the laboratory tests, the alkaline-activated material required approximately 24 hr with three applications of stripper. In addition, field service evaluations of the alkaline-activated stripper conducted at NADEP Jacksonville in April and December 1993 on gloss painted P-3C aircraft demonstrated similar results.

Since 1993, approval for limited use has been granted for three non-HAP chemical strippers to five sites for seven platforms. A non-HAP paint remover specification (TT-R-2918) was developed and released in early 1997. Recent reports from NADEP Jacksonville indicate greater difficulty in removing the coating systems from aircraft that have been repainted with self-priming topcoat (TT-P-2756) or with water-base epoxy primer (MIL-P-85582)/high solids urethane (MIL-C-85285). The hydrogen peroxide activated benzyl alcohol strippers are being evaluated to

address this deficiency. However, implementation is hampered by excessive corrosion rates for magnesium, titanium, and cadmium-plated steel and by waste handling concerns related to gas evolution in waste containers.

In order to comply with the 1998 NESHAP deadline, non-HAP chemical strippers, intended for metallic surfaces only, must be considered as an interim process as well as a supplemental process to the nonchemical technologies.

WATER TECHNOLOGIES

HIGH-PRESSURE WATERJET STRIPPING

The high-pressure waterjet process developed by Pratt & Whitney Waterjet (Huntsville, Alabama) employs high-pressure, low-volumetric flow rates for the removal of coating systems. Typically, water pressures in the 15,000 - 25,000 psi range are used with flow rates of less than 3.8 gal/min. Nozzles have been designed to provide a uniformly distributed stream of water, increasing the stripping efficiency of the process while reducing damage incurred during the stripping process. This is theoretically possible since the water is delivered to the surface at threshold energy levels required to remove the coatings (coating dependent) but not at a high enough energy level to cause substrate damage.

The mechanism for coating removal is similar to the mechanisms present during the rain-erosion of coatings on the leading edge of aircraft wings. However, in contrast to the uncontrolled erosion and damage from rain impact, the water's flow-dynamics and impact energies are controlled to increase the coating removal while maintaining damage-free substrate materials.

This method can be used to strip a variety of coatings from metal substrates, but has several limitations associated with it. First and foremost is the possibility of water intrusion into internal cavities where subsequent corrosion may be initiated. At these high pressures, seals, which offer excellent protection from water under normal operating conditions, do little to hold back the intense stream during direct impingement. Secondly, its use on very thin metallic substrates has been shown to cause serious substrate damage. Finally, the use on nonmetallic materials (organic matrix composites) has not been satisfactorily established for Navy applications. Initial testing showed a decidedly aggressive process that could be set for topcoat removal, but was unable to strip both the topcoat and primer without causing major damage to the composite substrate. Tighter control and greater design/stripping experience may eventually allow further use of high-pressure waterjet stripping in the future, but in its current iteration, this process is too unforgiving to allow its use on Navy aircraft.

A waterjet system is operational at Tinker Air Force Base (AFB) and has been used to depaint several different types of aircraft components including KC-135, B-1, and B-52's. The U.S. Air Force also had a significant effort in an advanced high-pressure water jet paint removal system. The "Large Aircraft Robotic Paint Stripping" program, run in conjunction with Pratt & Whitney Waterjet, was designed to establish an automated stripping process with the following characteristics: reduced aircraft preparation, cleanup, and depaint hours; reduced depot flow

times; reduced personnel exposure to hazardous waste production; and lower costs. This program centered around a fully automated high-pressure waterjet stripping system at the Oklahoma City Air Logistics Center (OC-ALC).

MEDIUM-PRESSURE WATERJET STRIPPING

The operational characteristics of a medium-pressure waterjet system are similar to those of a high-pressure system, but with nozzle pressures operating in the 10,000 – 15,000 psi range.

Warner Robins Air Logistics Center (WR-ALC) started investigating pressurized water paint removal methods in 1992 to replace methylene chloride based removers used for stripping paint from the C-130 and C-141 aircraft at Robins AFB, Georgia. This effort was targeted toward a modified MPW process that uses 15,000 psi of water injected with sodium bicarbonate to enhance the effectiveness of the process. Since the implementation of this process in May 1994, WR-ALC has documented an 87.7% reduction in the use of methylene chloride strippers. A materials properties evaluation was conducted to determine the effects of the modified MPW process on C-130 and C-141 aircraft substrates. Surface roughness, cladding erosion, fatigue life degradation, fatigue growth rate, shear strength of honeycomb core structures, peel strength, flatwise tensile, and flexural strength were evaluated[5]. WR-ALC determined that results were overall favorable, and the modified MPW process began production prototype work on the C-130 in November 1993.

The Navy has investigated the use of MPW without the injection of sodium bicarbonate. The use of this technology in conjunction with non-HAP's strippers may increase the effectiveness of the chemical paint strippers on the more difficult to remove paint systems and has been demonstrated on P-3 aircraft at Raytheon E-Systems, Greenville, Texas, with certain restrictions.[6] The MPW water application is capable of removing paint from engine containers and industrial equipment.

A medium-pressure waterjet investigation was also undertaken with the Concurrent Technologies Corporation, Johnstown, Pennsylvania. Graphite/epoxy panels manufactured identically to those used in both PMB and Flashjet® investigations were stripped using the upper limits of what could be referred to as medium pressure. Many trials were run at various machine settings. Variables studied included nozzle pressure (2,000 to 20,000 psi) and nozzle traverse speed (2 to 20 mm/sec). Variables held constant included nozzle rotation speed (500 RPM), standoff distance (2 in.), and impingement angle (90 deg). Table 2 summarizes the effort and qualitatively assesses each of the stripping trials. Of the 40 trials, only 3 were deemed acceptable (90% topcoat removal, no substrate damage), and each of these were panels stripped only to the primer. The operating parameters yielding acceptable results were as follows:

Nozzle Rotation Speed:	500 RPM
Standoff Distance:	2 in.
Impingement Angle:	90 deg
Nozzle Pressure:	15,000 psi
Nozzle Traverse Speed:	6, 8, 10 mm/sec

The results are consistent with those experienced while investigating the high-pressure waterjet system. The technology is capable of removing topcoats from primer/topcoat coating systems, but is unable to remove both topcoat and primer acceptably from composites. The technology operates with a severely limited cushion; one that is too small to risk use on Navy aircraft composite surfaces.

Table 2
CTC MEDIUM-PRESSURE WATERJET TESTING RESULTS

	Stripping Trial	Pressure (psi)	Rotation (RPM)	Speed (mm/sec)	Distance (in.)	Angle (deg)	Comments/Results
Panel 1							
	A	2,000	500	20	2	90	No paint removal
	B	5,000	500	20	2	90	No paint removal
	C	10,000	500	20	2	90	No paint removal
	D	15,000	500	20	2	90	Severe panel damage
	E	14,000	500	20	2	90	Severe panel damage
	F	13,000	500	20	2	90	Severe panel damage
	G	12,000	500	20	2	90	Severe panel damage
Panel 2							
	A	20,000	500	20	2	90	Severe panel damage
	B	15,000	500	20	2	90	Slight removal of topcoat, pronounced swirl pattern
	C	16,000	500	20	2	90	Topcoat and slight primer removal, some panel damage
	D	17,000	500	20	2	90	Severe panel damage
	E	18,000	500	20	2	90	Severe panel damage
	F	19,000	500	20	2	90	Severe panel damage
	G	20,000	500	20	2	90	Severe panel damage
	H	15,000	500	10	2	90	Good topcoat removal, primer intact, no panel damage
	I	16,000	500	10	2	90	Topcoat and slight primer removal, severe panel damage
	J	17,000	500	10	2	90	Severe panel damage
	K	15,000	500	2	2	90	Severe panel damage
	L	15,000	500	8	2	90	Good topcoat removal, primer intact, no panel damage
	M	15,000	500	6	2	90	Topcoat and slight primer removal, some panel damage
Panel 3							
	A	15,000	500	4	2	90	Topcoat and slight primer removal, some panel damage
	B	15,000	500	10	2	90	Slight removal of topcoat, pronounced swirl pattern
	C	15,000	500	8	2	90	Fair topcoat removal, primer intact, no panel damage
	D	15,000	500	6	2	90	Good topcoat removal, primer intact, no panel damage
	E	15,000	500	4	2	90	Topcoat and slight primer removal, some panel damage
	F	15,000	500	2	2	90	Severe panel damage
	G	17,000	500	10	2	90	Severe panel damage
	H	17,000	500	20	2	90	Severe panel damage
	I	17,000	500	30	2	90	Severe panel damage
	J	17,000	500	40	2	90	Severe panel damage
Panel 4							
	A	16,000	500	10	2	90	Good topcoat removal, primer intact, some panel damage
	B	16,200	500	10	2	90	Severe panel damage
	C	16,400	500	10	2	90	Severe panel damage
	D	16,600	500	10	2	90	Severe panel damage
	E	16,500	500	10	2	90	Severe panel damage
	F	16,300	500	10	2	90	Severe panel damage
	G	16,300	500	10	2	90	Severe panel damage
	H	16,000	500	10	2	90	Severe panel damage
	I	15,900	500	10	2	90	Severe panel damage
	J	15,800	500	10	2	90	Severe panel damage

PLASTIC MEDIA BLASTING

PMB is a mature, production-ready process that is more environmentally friendly than chemical stripping and reduces operator exposure to health hazards. Studies conducted by NAWCAD Patuxent River[7,8] showed that surface erosion of unidirectional graphite/epoxy composite was the mode of damage. As a result, any reduction in mechanical properties would be more easily detected in a thin test sample than in a thicker one, due to the eroded material accounting for a larger percentage of the specimen's cross-sectional area. Subsequent studies[9] using 0.073-in. thick, 14-ply panels identified a "window" of safe operating parameters for paint removal from graphite/epoxy composites without adversely affecting the mechanical integrity of the substrate material. The Navy issued a specification for "Plastic Media for Removal of Organic Coatings", MIL-P-85891. Of the seven types of media described in the specification, Type V (acrylic media) has the potential for safe and efficient removal of coatings from Navy aircraft and is in use at the NADEP's. Type VII (starch-acrylic), a recent addition, is a product that can be used to blast fiberglass structures without damage to the substrate.

The PMB process was approved by NAVAIRSYSCOM for use at depot-level activities to remove paint from aluminum airframe surfaces of 0.016-in. minimum thickness and from composite laminate aircraft surfaces of 0.073-in. minimum thickness. While PMB is well suited for aircraft paint stripping, significant amounts of waste are generated, and the process does not meet the environmental goal of minimizing hazardous waste.

PLASTIC BLAST MEDIA TREATMENT

In 1993, PMB gained increasing usage as the Navy's only approved aircraft depainting method not requiring the use of hazardous chemicals. The use of PMB generates significant quantities of waste, consisting of spent (under size) media, which are intimately mixed with paint particles and metallic contaminants. Waste disposal costs for paint stripping at NADEP Jacksonville were $850,000 in FY94, of which PMB waste was the largest contributor. Studies were conducted from FY93-FY94 to evaluate alternative methods of treatment and disposal of aircraft depainting waste for the depots to meet the Navy's hazardous waste reduction mandate. The approach involved identification of alternative methods, demonstration at NADEP Cherry Point, and transitioning to the fleet through the use of specification and design modifications. Efforts were coordinated by the Navy, Air Force, and industry.

Disposal options for PMB waste were evaluated as follows:

1. Removal/contamination prevention. - Efforts to segregate blast media and to test each drum prior to any mixing of media were unsuccessful. The costs of testing and monitoring could not be justified.

2. Manufacture of new products from media blast residue. - Discussions were held with North Carolina State University and Pennsylvania State University concerning utilization of spent plastic media in the manufacture of highway sign posts. NADEP Cherry Point contracted with Pennsylvania State University to evaluate processing

temperature requirements, materials properties of manufactured specimens, and a comparison of the materials properties against those of pressure-treated lumber. Specimens were manufactured using a combination of spent and virgin media. However, strength properties were exceptionally low, restricting potential utilization of this material.

3. Lease/sell-back options for acrylic plastic media. - Three plastic media manufacturers were contacted concerning lease/sell-back options. The EPA concluded that the only acceptable means available for eliminating spent media as a hazardous waste stream is for the spent media to be used as a beneficial raw material in the manufacture of a new product. A U.S. technology proposal to lease the media to the government and to use the spent media to manufacture cultured marble fixtures was approved by the EPA and numerous state environmental agencies. Coordination with General Services Administration (GSA) was maintained since plastic media was traditionally procured through the GSA, which recommended that initial lease contracts be let by facilities agency-wide. NADEP Cherry Point and NADEP Jacksonville established lease agreements for the return of spent media to the supplier, with approval of EPA authorities. These arrangements contributed to the reduction of hazardous waste disposal at the depots.

WHEAT STARCH BLASTING

Wheat starch blasting is an abrasive blasting process with different media. Instead of dry blasting particles of plastic, purified wheat starch is used for stripping. The media is both biodegradable and nontoxic in nature and can be substituted into current PMB blasting equipment with a few modifications. The material is known to be less aggressive than Type V media, which in turn leads to slower coating removal rates. The tradeoff between strip rate and biodegradability, however, will become more and more attractive as disposal of plastic media dust increases in cost, and if commercial "bioreactors" (continuous biodegradation of used media) become available for disposal of the spent wheat starch media.

Wheat starch media requires a "break-in" period before it begins to strip at an acceptable rate. This break-in period, consisting of nothing more than blasting with the media for several cycles through the machine, allows the media to break down slightly into smaller more angular particles better suited to eroding away the desired coating. Because of this phenomenon, blasting equipment is initially charged with media ranging in sieve sizes between 30 and 100 mesh. Subsequent additions to the system are made with larger 12-30 sieve size media.

Wheat starch blasting has the advantage of being effective in the removal of elastomeric coatings. Thick rain-erosion coatings present on fiberglass composites could not be stripped using PMB because the media simply bounced off the surface of the coating. Initial results have shown that wheat starch blasting not only removes the coatings, but does so in a substantially safer manner than the previous combination of chemical stripper and brass scrapers.

Wheat starch has inherent drawbacks. Aside from its relatively slow removal rate of 0.3 to 0.9 ft^2/min, the use of wheat starch in high humidity environments, such as NADEP Jacksonville or Cherry Point is a concern. Humidity in excess of 60% RH can lead to media clumping, which in turn can lead to uneven flow or, at worst, machine clogging with subsequent shutdown. In order to combat this potential problem, thoroughly dried air must be supplied to the blast equipment. The addition of the air drying unit to standard PMB blasting equipment is the only large capital investment required to convert a PMB system into a wheat starch system.

A secondary but serious possible drawback to the wheat starch media is media intrusion and subsequent mold formation within the aircraft once fielded. No matter how diligently aircraft are masked and sealed prior to media blasting (plastic media, wheat starch, bicarbonate of soda, etc.), media will find a means of entering the aircraft structure. This media then becomes a permanent part of the aircraft, and wheat starch's proclivity for mold germination can lead to onboard mold contamination.

As previously mentioned, a pilot scale "bioreactor" has been developed. This reactor would use the spent media as "food" for the bio organisms, separating the "edible" wheat starch from the inedible coatings, thereby reducing generated waste to only the removed coatings. This technology, originally designed for batch processing, could be upgraded to a semi or continuous process if economically justified.

Research conducted by the Defense Research Establishment Pacific of Canada investigated the effect of multiple-paint removal cycles on AS4/3501-6 graphite/epoxy composite substrates. In general, an obvious increase in strip rate was noted as increasingly aggressive blast parameters (higher pressures) were used. A significant reduction in the stripping rate after completion of the first removal cycle was noted under all blast conditions, with smaller reductions in stripping rate occurring for subsequent cycles. Media breakdown to the point beyond which stripping efficiency would decrease will not occur following a single blast cycle; therefore, the decrease in strip rate was attributed to changes in the surface layer of the composite after initial blasting, allowing greater primer adhesion in subsequent paint/blast cycles.

Microscopic examination of panels blasted under the most severe conditions (four paint/blast cycles, 276 kPa, 18 cm standoff, and a flow rate of 227 Kg/hr) indicated that the top resin layer (gel coat) was still intact with no exposed fibers visible. Four-point flexure tests indicated that there was no significant difference in the failure stress between the blasted and unblasted surface for two panels stripped under the following conditions: Panel 1 – 276 kPa, four paint/strip cycles; Panel 2 – 172 kPa, one paint/strip cycle.

Wheat starch blasting was not selected as a long-term solution to the problem of environmentally friendly paint removal methods for Navy aircraft because of slow removal rates, moisture sensitivity, and media intrusion with possible subsequent mold formation, combined with a large waste stream made up of both media and coating residue.

XENON FLASHLAMP/CARBON DIOXIDE COATINGS REMOVAL PROCESS

BACKGROUND

The Xenon flashlamp/CO_2 coating removal system reflects a synergistic coupling of two diverse approaches (high-intensity flashlamp exposure/CO_2 pellet blasting) to aircraft paint removal. Neither method, when viewed alone, allowed for safe and effective coating removal from aircraft substrates. Flashlamp coating removal was initially investigated by the Sacramento Air Logistics Center in 1987 and was deemed unacceptable due to lamp reliability, soot residue, substrate heating, etc. CO_2 pellet blasting was similarly investigated in 1990 by WR-ALC[10]. The technology is extremely slow, as well as potentially damaging to composite and thin aluminum skins. McDonnell Douglas Aerospace (MDA), currently Boeing St. Louis, under contract to WR-ALC, developed and patented a concept in 1991 known as Flashjet®. The process combines the flashlamp-induced coating volatilization followed by the sweeping motion of the low-pressure CO_2 particle stream that acts as a soot remover, lamp cleaner, and substrate cooler.

In 1992, WR-ALC sponsored a Producibility, Reliability, Availability, and Maintainability (PRAM) contract with MDA, Cold Jet, and Maxwell Labs for the development and demonstration of a prototype (6 in.) Flashjet® system for use on F-15 composite parts coating removal. The program was successfully completed with the stripping of an F-15 boron/epoxy composite vertical stabilizer; at which point, a larger (12 in. – production sized) Flashjet® unit was developed. Subsequently, the U.S. Air Force contracted MDA to conduct extensive paint removal investigations over the next 14 months.[11]

The U.S. Navy became involved in this effort in 1992 when a teaming with WR-ALC allowed for maximization of research, development, test, and evaluation funds. Navy-specific materials and requirements were outlined for this add-on effort, conducted by MDA, and focused mainly on metallic substrates with limited initial investigation of composite materials[12]. The initial program was completed in 1993, and a follow-on testing program focused exclusively on nonmetallic aircraft structural materials and was completed early in 1996[13], under the Aircraft Depainting Technology Program. Results of the testing programs are described on page 15.

FLASHJET® SYSTEM OPERATION

The pulsed light energy source, a xenon flashlamp, consists of a 12-in. long quartz tube filled with xenon gas that when energized, emits short pulses of intense, broad-band light. As the coating absorbs this photon energy, its temperature rises rapidly to the point at which a thin layer is ablated (eroded). Rapid pulsing of the lamp while the stripping head traverses the part results in excellent coating removal rates with no damage to the substrate materials. As the coating undergoes ablation, the resulting residue is simultaneously swept from the surface by the low-pressure dry ice particle stream and collected by the effluent capture system. The heating effect of the photon energy is continually being offset by the cooling effect of the dry ice particle flow. As a side benefit, the CO_2 environment under the stripping head provides an atmosphere, which will not support combustion of flammable surface contaminates.

The *amount of paint removed* from an area of substrate is approximately proportional to the energy delivered to the area, so the *rate of removal* is proportional to the power. A discreet total energy is required to remove 5 mils of paint from 1 ft^2 of substrate. This energy can be applied more or less rapidly by operating at higher or lower input voltage and pulse rate with the correspondingly shorter or longer removal rates. A separate variable, which can be used to vary the removal rate, is the stripping-head traverse rate. A given energy can be delivered to an area by operating at high input voltage at a rapid traverse rate, or by using a lower input voltage and moving the head more slowly. A slower removal rate may provide finer control over the strip depth and minimize heating of delicate substrates.

A major advantage the Flashjet® system has over other coating removal methods is the degree of control achievable. Through adjustment of the operating parameters (i.e., light-energy density, traverse rate, etc.) varying degrees of coating removal are possible, including complete coating system (topcoat and primer) removal or topcoat only removal. This selective coating removal is extremely attractive for composite substrates, whereby leaving the primer intact precludes any possible substrate damage.

FLASHJET® SYSTEM DESCRIPTION

The Flashjet® system is comprised of the following subsystems:

1. Control Console.
2. Power Module.
3. Dry Ice Delivery System.
4. Liquid CO_2 Storage Facility.
5. Compressor.
6. Stripping Head.
7. Effluent Capture System.

A brief description of the purpose, requirements, and capacities of each subsystem is as follows:

1. Control Console: Process control and input parameters are managed at the control console, which enables the operator to operate the entire stripping process from a single location.

2. Power Module: The power module provides the 480 V, 100 amps, 3-phase energy requirement needed to operate the flashlamp.

3. Underlined: CO$_2$ Delivery System: The dry ice particle delivery unit consists of a pelletizer/blast unit that manufactures pellets from liquid $CO_2$and delivers them to the stripping head at a rate of ≈ 750 lb/hr.

4. Liquid CO_2 Storage Facility: A liquid CO_2 storage tank is required as part of the CO_2 pellet subsystem. Several options exist to fill this requirement, such as permanent installations, portable installations, or utilization of transport trailers as a storage facility. Proper CO_2 refrigeration and pressure must be maintained at all times.

5. Compressor: The compressor supplies high capacity air (750 CFM at 150 PSIG) to the CO_2 pellet subsystem.

6. Stripping Head: The stripping head contains a 12-in. flashlamp and reflector, an effluent capture system, and CO_2 delivery nozzles. A color sensor system is located on the head to detect primer/bare substrate. Motion and proximity sensors are also mounted on the stripping head (figure 1).

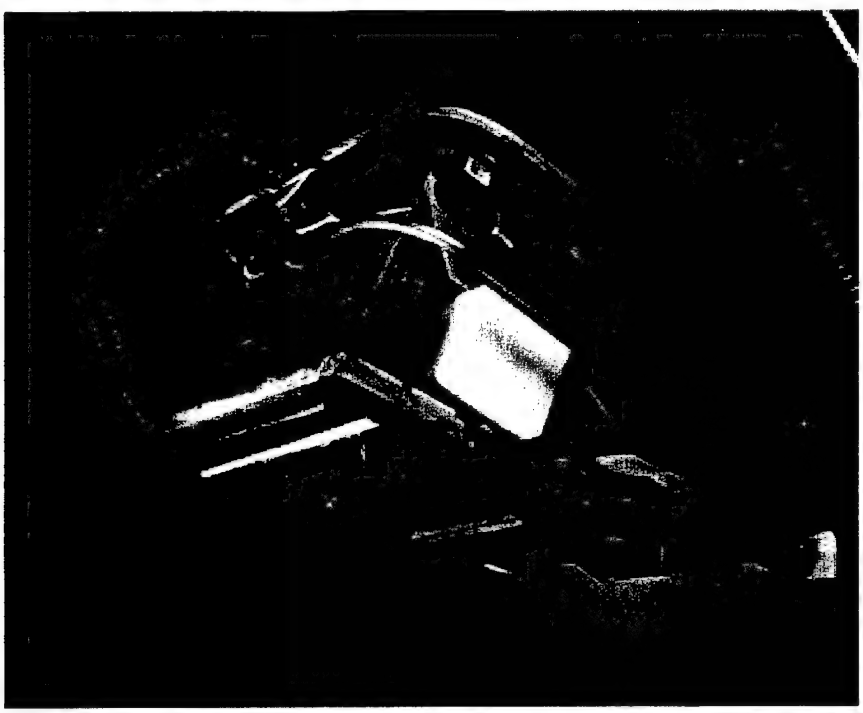

Figure 1
FLASHJET® STRIPPING HEAD

7. Effluent Capture System: The effluent capture system consists of the containment shroud (located on the stripping head), a high-volume vacuum source, a particle separator, pre- and HEPA filters, and an activated charcoal air scrubber.

COMPARISON OF AIRCRAFT PAINT REMOVAL PROCESSES AND DOWNSELECTION

Under the Aircraft Depainting Technology Program, a comparison was made of emerging technologies that could be adapted to paint stripping production quantities of aircraft in the near term of 1-3 years. Requirements for candidate technologies were as follows:

1. Environmentally safe and effective to provide compliance with upcoming federal and local regulations.

2. Nondamaging to aircraft metallic and composite surfaces.

3. Efficient and cost effective.

4. Minimizing the production of hazardous waste.

The basis for comparison of environmentally safe and effective processes was the historical process of chemical stripping with methylene chloride based paint removers. This process was compared with the other production ready processes described above; namely, non-HAPS Chemicals, PMB with Acrylic Media, Wheat Starch, Flashlamp/CO_2 (Flashjet®), and Pressurized Water Technologies. A matrix was developed to provide an overview of critical characteristics of the above viable processes, as shown in table A-1. The matrix depicts pertinent characteristics of emerging aircraft paint stripping technologies for the near term. Other technologies involving lasers, microwaves, or photochemical techniques were still in the developmental stages and not sufficiently advanced for full-scale aircraft paint stripping in the time frame by which increasingly stringent federal and local regulations would take effect.

Comparison shows that the flashlamp/CO_2 process reduces the hazardous waste stream more than any other process and provides a minimum of preparation time and post-strip cleanup, with a reduction in throughput time and a high strip rate. The stripping cost per square foot for alternative technologies was provided by facilities conducting aircraft paint stripping and varies with weapons systems, location, local requirements, and other factors. As a preliminary comparison, the flashlamp/CO_2 process is seen to be cost competitive with other processes. As the program progressed, a detailed cost benefit comparison was developed and is described further in this report. Flashjet® process variables can be more closely controlled than other methods that rely on operator controls. On the basis of the comparative analysis, downselection was made for a detailed study of the effects of the flashlamp/CO_2 process on metallic and composite aircraft surfaces and for investigation into the methods for transition of the process for Navy aircraft paint stripping.

EFFECTS OF THE XENON FLASHLAMP/CARBON DIOXIDE PAINT REMOVAL PROCESS ON AIRCRAFT STRUCTURAL MATERIALS

BACKGROUND

A primary concern in choosing a paint stripping method for aircraft is whether the method will cause any damage or degrade the properties of the underlying metallic or composite substrate. Extensive tests of the xenon flashlamp/CO_2 system were conducted under Air Force and Navy supervision. Under the U.S. Air Force PRAM project, open-hole compression testing of boron/epoxy and fiberglass laminates was performed. The test results[11] revealed that neither composite material showed any signs of mechanical property degradation caused by the process when the specimens were selectively stripped of the topcoat and leaving the primer intact, which is the recommended method for stripping composites. Additional testing sponsored by the Strategic Environmental Research and Development Program (SERDP) was conducted under the referenced U.S. Navy Add-On Program[12] and U.S. Navy Follow-On Program[13]. These tests indicated that the xenon flashlamp/CO_2 process can selectively remove paint systems down to paint primer or to the substrate without damaging impact on the mechanical properties of thin, structural aluminum alloys; the mechanical properties of various carbon/epoxy layups; adhesive bond strength; and butt joint gap sealant. In the Navy test program, paint was removed either to the primer or the substrate, or stripped to an abusive saturation condition by increasing the normal dwell time to remove paint to the substrate. The following paragraphs summarize results of the Navy test programs.

Test results showed that the xenon flashlamp/CO_2 process is benign to aluminum alloy substrates. Maximum Almen strip deflection was 0.5 mils using worst-case CO_2 parameters. Almen strip deflection is a measure of residual stress induced by surface impact. A deflection of 0.5 mils shows an essentially negligible effect of CO_2 particle impact for the low pressures and angle of attack used in the process. By comparison, PMB produces deflections 5 to 10 times higher. Coating removal strip rates were optimized for four different paint systems and determined to be 2.0 to 4.0 ft^2/min to the primer and 1.6 to 2.8 ft^2/min to the substrate. Climbing drum peel testing of bonded aluminum skin-aluminum core sandwich assemblies and lap shear testing of bonded finger panels were used to evaluate the effects of removing paint on the adhesive bond strength of three different adhesive systems used by the U.S. Navy. Analysis of test specimens and results indicated that the xenon flashlamp/CO_2 process does not affect the adhesive bond strength of the specimens.

Spectrum metal fatigue life tests were conducted on A1 2024-T3 and A1 7075-T6 bare and clad material using open-hole and unnotched crack initiation specimens and crack growth specimens. Stripped specimens did not show a statistically significant difference from the pristine baseline material.

Longitudinal flexure, tension, compression, and open-hole fatigue tests were performed to study the effects of the stripping process on the residual strength of AS4/3501-6 graphite/epoxy composites. The data were compared against baseline data of unstripped, unpainted specimens to

determine if any damage had occurred from the stripping process. Additionally, since Flashjet® is a thermal process, substrate temperatures were monitored during the stripping process to assure no excessive temperature excursions had occurred.

Each panel used for the mechanical testing was one of two specific layups. For the longitudinal four-point flexure tests, a surface sensitive layup $[0°_2, \pm45°, 0°, \pm45°]_s$ was used. Its failure mode is the surface ply on the compression side of the specimen and allows for detection of small changes in surface damage through reduction in strength. The tension, compression, and open-hole fatigue specimen layup was $[67.5°, \pm22.5°, -67.5°, \pm22.5°, 67.5°]_s$. Each configuration was derived from previous PMB investigations that allowed direct comparison of the two methods.

All panels used for this project were coated with then standard military epoxy primer (MIL-P-23377, 1 mil), and polyurethane topcoat (MIL-C-83286, 2 mils). Panels were then aged for 1 week at room temperature followed by 1 week at 150°F. All mechanical testing was carried out for the following coating removal conditions: *Baseline* – unpainted, unstripped specimens; *To Primer* – removal of topcoat only (mottled surface with ≥ 50% primer layer visible showing); *To Substrate* – removal of topcoat and primer layers down to graphite/epoxy substrate (mottled surface with ≥ 50% substrate layer visibly showing); and *Saturation* – strip to "*To Substrate*" condition and add an additional two-thirds the number of passes required to reach the "*To Substrate*" condition. (Example: If it takes three passes to remove the coating system to the "*To Substrate*" condition, exposure of the panel to the "*Saturation*" condition would require an additional two passes.) This last condition was created to simulate worst-case potential overlap during repositioning of the stripping head.

FOUR-POINT FLEXURE TEST

Two laminates (28 x 30 in.) were manufactured simultaneously and subjected to the same environmental conditioning during processing. Both laminates were ultrasonically inspected and subsequently machined into twelve 10- x 12-in. panels (six from each laminate). Panels used for tension, compression, and fatigue were likewise fabricated. A group of painted panels from the second laminate was stripped using a "low energy" setting on the flashlamp, and a second group from the second laminate was stripped using a "high energy" setting. There were 48 specimens (12 *baseline*, 12 "*to-primer,*" 12 "*to-substrate,*" and 12 "*saturation*") machined from panels stripped using "low energy." An additional 48 specimens were machined from panels stripped using "high energy." All "low power" stripped specimens exhibited no statistically significant change in flexural strength after exposure to the Flashjet® process. The "high power" stripped specimens showed a statistically significant decrease of –1.7% in the "*to-substrate*" condition only.

TENSION TEST

Tension tests (compression and fatigue tests as well) were performed on 14-ply unnotched specimens. Fiberglass tabs were bonded to the tension test sections of the baseline and stripped panels. A biaxial and a uniaxial strain gauge were bonded to the 48 tension specimens (12 *baseline*, 12 "*to-primer,*" 12 "*to-substrate,*" and 12 "*saturation*"). Statistical analysis

indicated that no significant difference existed in the tensile strength or Poisson's ratio between the stripped specimens and the unstripped baseline specimens. Tensile modulus exhibited a statistically significant increase of +0.2% for the "*to-substrate*" condition.

COMPRESSION TEST

A total of 48 specimens (12 *baseline*, 12 "*to-primer,*" 12 "*to-substrate,*" and 12 "*saturation*") were tested in compression. A "Reiling" compression support fixture was used to reduce the tendency of the specimen to fail outside the desired test area. Statistical analysis indicated that no significant difference existed in the compression strength, compression modulus, or Poisson's ratio between the stripped specimen and the unstripped baseline specimens.

OPEN HOLE FATIGUE

All specimens were tested under constant amplitude tension/compression (R=1) at a loading of 60% of ultimate and a cycle rate of 4 Hz. At this cycle rate, specimens were heated to approximately 7°F above room temperature at failure. Statistical analysis indicated that no significant difference existed in fatigue life for the "*to-primer*" and "*saturation*" conditions, with a slight (-1.3%) decrease observed for the "*to-substrate*" condition.

QUALIFICATION OF THE FLASHJET® PROCESS

As a result of the materials testing described above, NAVAIRSYSCOM authorized the use of the Flashjet® paint removal process for removing organic coatings from metallic fixed-wing aircraft surfaces, such as a P-3 aircraft. The approval process for use of Flashjet® on fixed-wing organic composite aircraft surfaces initiated under this program is nearly complete and requires only sonic fatigue tests relative to the F/A-18E/F aircraft. High cycle fatigue tests for use of the process on aluminum alloy helicopter fuselage skin have also been initiated under a joint service project funded by the Environmental Security Technology Certification Program and the CNO N45 Aviation Pollution Prevention Technology Program.

COST BENEFIT COMPARISON OF AIRCRAFT DEPAINTING METHODS

BACKGROUND

Paint stripping remains one of DOD's most costly aircraft maintenance processes. Paint stripping costs are influenced primarily by labor costs tied to throughput time, cost of facilities and equipment, cost of materials, cost of hazardous waste, and air pollution control equipment. Chemical paint stripping is one of DOD's most wasteful and potentially polluting processes. Common methylene chloride based paint strippers' purchase cost is between $4 to $8 per gallon while the non-HAP's chemical paint removers typically cost $10 to $20 per gallon. While plastic media purchase costs are typically $1.50 to $2.00 per pound, hazardous waste disposal costs must be considered. Plastic media leasing has offered aircraft depots a means to remove the tons of

used plastic media from hazardous waste classification and documentation; however, leased plastic media cost is at least the same or slightly more costly than the price to purchase the media and dispose of it as hazardous waste.

Hazardous waste disposal costs vary greatly among DOD industrial facilities. NADEP Jacksonville pays about $1.30 to $1.50 per pound for disposal of all types of hazardous waste. WR-ALC pays $2 per pound for paint stripper disposal while paying only 27 cents per pound for blast media disposal. While NADEP Jacksonville is paying approximately $1.50 per gallon to treat waste water from their chemical stripper operation, WR-ALC pays only 1 cent per gallon.

When comparing costs incurred using chemical, media, or light energy based depainting technologies, the prestrip and poststrip process steps and costs must also be considered. Flashjet® and laser processes offer the capability to selectively remove paint and primer, one layer at a time. Of all the depainting technologies evaluated in this study, Flashjet® was the most mature in its capability to remove paint one layer at a time. Repriming processes can thereby be eliminated where applicable.

AIRCRAFT DEPAINTING COST COMPARISON MODEL

The initial survey shown in the Alternative Paint Removal Technology Matrix (table A-1) was based on several different methods and available data elements. In 1996, this project began the use of a detailed cost comparison software that accounted for the total paint removal cost, including prestrip and poststrip operations. Table A-2 contains revised cost results contained in the Air Force Depaint Cost Comparison Model (©1998 USAF Depaint Cost Comparison Model v2.0), based on 50 aircraft/year. This model contains data falling into the general categories of flow time, material cost, labor costs, waste disposal costs, and process implementation costs. The results in this table provide an estimated life cycle cost per square foot comparison of the most common depainting technologies (PMB and methylene chloride chemicals) with the Flashjet® process in a robotic or semirobotic application. The cost data used in this revision of the model are a rough average of the range of materials, labor, energy, and waste costs seen at DOD Aviation Maintenance Depots. Data could vary significantly at individual depots. Ultimately, the numbers are most valuable as an index to show relative life cycle costs of depaint technologies. The intent of this table is to assist program and facilities managers in making more informed decisions on depainting technology investment. The software can be tailored to a specific facility or aircraft. More information is available from Mr. Randall Ivey, Chief, Materials Engineering Section, WR-ALC/TIEDM, Robins AFB, Georgia, 31098-5940 (Telephone (912) 926-4489).

APPLICATION OF FLASHJET® COATINGS REMOVAL TO LARGE AIRCRAFT

PRIOR EFFORTS

As described above, an Air Force PRAM-funded project for development of the Flashjet® system evolved into a joint Navy/Air Force project for detailed test and evaluation of the process. Boeing, St. Louis, invested corporate funds to transition this technology to a mature, production ready status using robotic controls. In separate but related evaluations, WR-ALC awarded a

program to Mercer Engineering Research Center (MERC), 135 Osigian Blvd., Warner Robins, Georgia, 31088-7810, to demonstrate the potential of semiautomated assisting devices for improving the productivity and cost effectiveness of advanced depainting processes. MERC performed a preliminary design and documented the feasibility of a manipulator system. As a result, the Air Force funded a second phase with MERC to develop a prototype dual-arm manipulator system. The prototype proved that the positioning and automated manipulation of the depaint end effectors could be achieved with the dual-arm system. This prototype also showed that productivity using a manipulator system could be eight times greater than that of a normal system.

THE MANIPULATOR CONCEPT

The Manipulator Arm System (MAS) is a multipurpose device to assist in semiautomatic manipulation of aerospace equipment. The initial concept was based on the need to accurately position and automatically manipulate aircraft paint stripping nozzles. The MAS can be used effectively with all systems that require accurate positioning against a surface and can be maneuvered over the surface in multiple passes. Various applications are being investigated, including depainting, nondestructive inspection, and component mapping. The system consists of four main components: platform, multifunctional dual manipulator arms, traverse, and controller.

The platform is designed to support an operator and interface devices. The primary interface devices selected are a joystick, touch screen, and video monitor. The joystick is used to assist the operator to position the system against the work surface. The joystick is used for all manual manipulation of the arms or to traverse the end effector. The touch screen is the primary interface with the controller used to select the operating modes, adjust parameters, and indicate all warnings and communications to and from the controller. The operator is allowed to change traverse speed, traverse distance, arm travel direction, and distance between passes. The video monitor is used to give the operator visual feedback of the action on the surface.

Dual manipulator arms are used to give the system its primary maneuverability. The arms are controlled hydraulically, using servo valves to regulate the flow of hydraulic fluid. There are four cylinders, two for extension and two for arm rotation, and all four are equipped with feedback devices. A traverse is used as the connection point for all end effectors that will be used. This consists of a mounting table, slides, ball screw, and motor to drive the system. The accuracy of positioning and speed allow the system to be used for virtually any application. The controller consists of all the electronics needed to operate the system. The power supply for all components is also routed and controlled here. The controller consists of an industrial PC-based computer and Delta Tau card. These two devices work in conjunction to process inputs, analyze feedback devices, and send output signals to all components.

SECOND GENERATION MANIPULATOR ARM/VEHICLE FABRICATION AND FLASHJET® INTEGRATION

Under the sponsorship of the SERDP and the Office of Chief of Naval Operations Environmental Protection, Safety, and Occupational Health Division (N-45), the Navy conducted a series of programs to demonstrate the application of a mobile, vehicle integrated manipulator with a Flashjet® system capable of providing sufficient reach to demonstrate the paint removal process on a Navy P-3 aircraft. WR-ALC supported this program by providing engineering support and excess Cold Jet CO_2 pellet blasting equipment and some Flashjet® hardware remaining from previous developmental efforts. In May 1995, contract F09603-93-G-0012-Q608[14] was established with MERC to develop a manipulator arm capable of operation in a production environment and to implement changes identified from previous prototype efforts. The project required the demonstration of positioning and manipulation of advanced depainting equipment for removing coatings on large aircraft. In December 1995, contract F09603-93-G-0012-Q610[15] established an expanded effort to design and integrate a vehicle interface for the MAS and to study the integration requirements to attach a Boeing Flashjet® depaint system to the latest version of the MAS under development. Under these efforts, a heavy duty fork truck lift vehicle was procured and integrated with the MAS system. A subcontract was issued to Boeing to study Flashjet® integration issues and design the integration concept. At the completion of the study[16], it was determined that the Flashjet® system could be mounted to the MAS; however, modifications to the operator station and MAS system would be required. The changes would incorporate the Flashjet® pendant in the operators station, redesign stripping head brackets, modify software, redesign the stripping head shroud and its attachment to the MAS, redesign the MAS traverse attachment points, and modify the vehicle festooning assembly. Integration requirements to fully operate and strip aircraft surfaces using the 12-in. Flashjet® system mounted on the MAS were determined.

Preliminary testing of the MAS and vehicle using a mockup of the Flashjet® was also completed. Results at this stage were successful, but a potential problem interfacing with the Flashjet® was identified. The problem concerned EMI interference effecting the position indicators on the arm axis of rotation. Interference to the rotational sensor would have caused tolerance errors in the controller that would have created an emergency stop condition on the MAS. A new set of EMI resistant sensors was provided. The net results at this point were that an integrated MAS and vehicle with the mobility to position the platform about an aircraft was designed and prototyped and Flashjet®-to-MAS integration requirements were identified.

FLASHJET® EQUIPMENT PROCUREMENT AND INTEGRATION TO THE MANIPULATOR ARM SYSTEM

Contract F09603-93-G-0012-Q612[17] was established to procure a Flashjet® power supply and lamp head assembly, design a stripping head/pendant for MAS integration, and to design and implement MAS changes established by the previous studies.

A final contract, F09603-93-G-0021-Q615, was issued in June 1997 for the final assembly and integration of the Flashjet®, manipulator, and vehicle system. This project involved the mounting, integration, checkout, and demonstration of a Boeing Flashjet® depaint system on the developmental model of the MERC MAS. This contract completed the design, procurement, fabrication, and assembly of all components to mate a Flashjet® depaint system to the manipulator arm. Tasks completed procurement of all services and material from major systems suppliers, Boeing, Cold Jet, and MERC. In addition, final integration of the total system, training, and checkout at NADEP Jacksonville were completed in anticipation of technology demonstrations on the Orion P-3 aircraft. The Flashjet® mobile manipulator system for depainting large aircraft is illustrated in figures 2 and 3. Figure 2 shows the operator-controlled MAS system, and figure 3 illustrates access of the system to a P-3 aircraft.

The system technology demonstration was conducted in June 1998 validating the paint stripping concept for large aircraft. Video documentation of the demonstration is available from Communication Services, Code 7.2.4.5.0, NADEP Jacksonville, Florida.

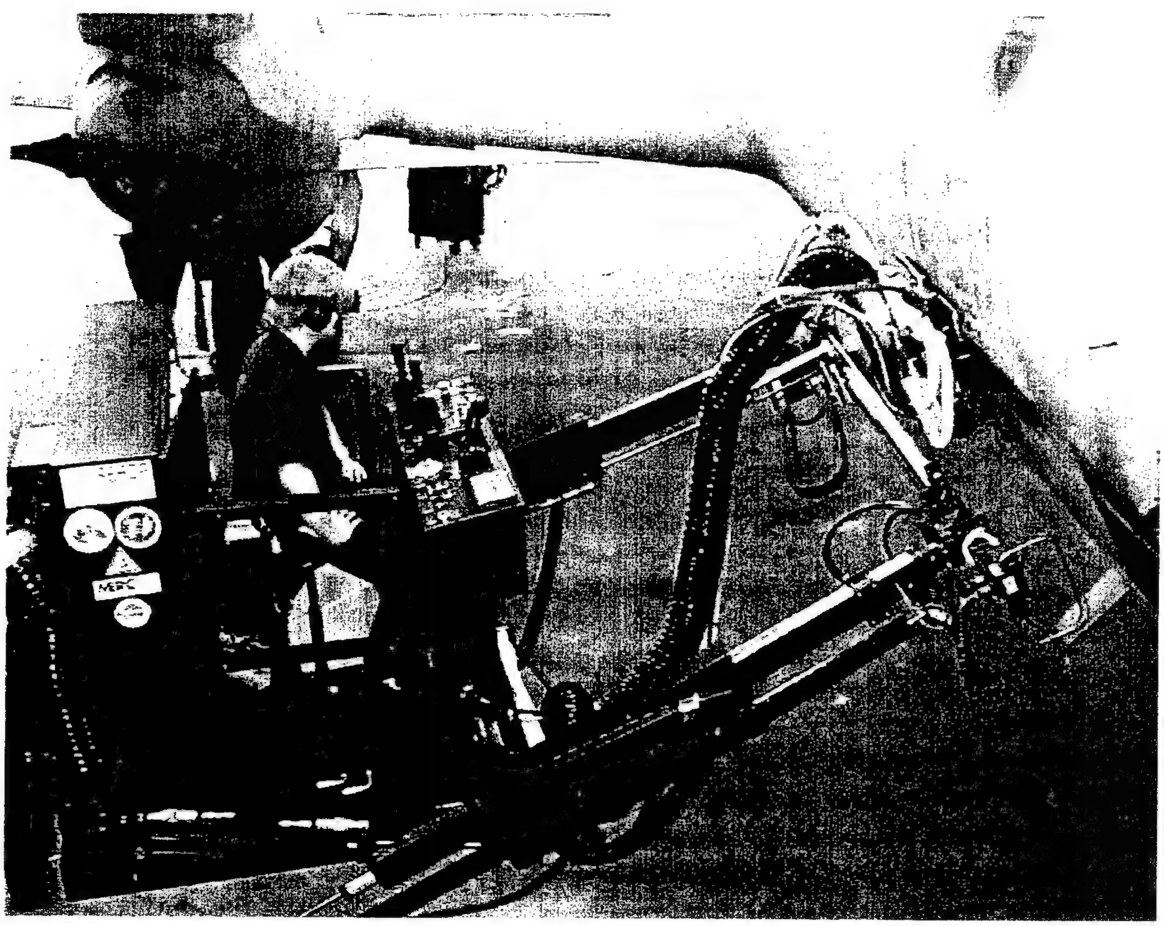

Figure 2
PROTOTYPE MOBILE APPLICATION OF FLASHJET® FOR P-3 AIRCRAFT
AT NADEP JACKSONVILLE

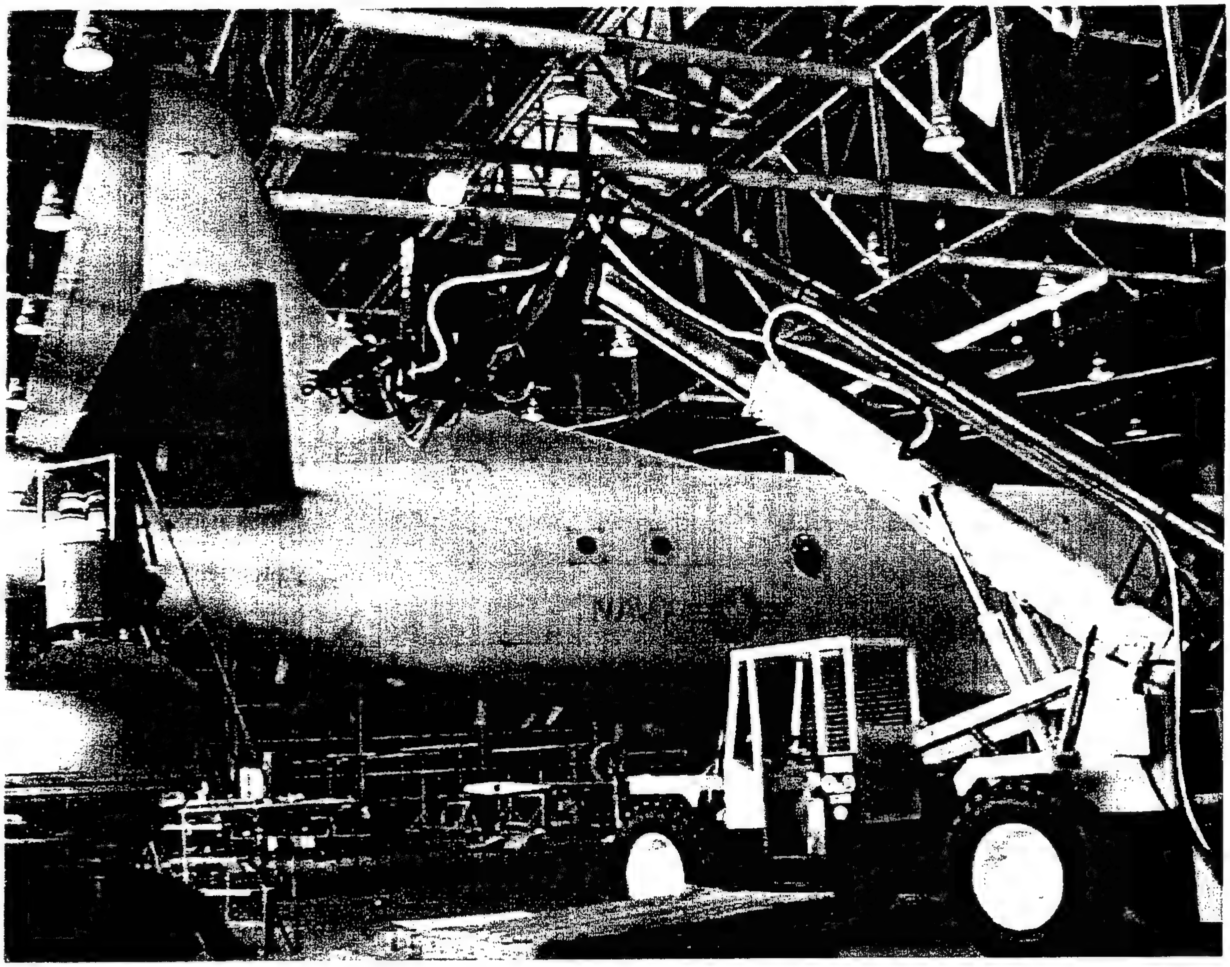

Figure 3
HIGH REACH CAPABILITY OF THE PROTOTYPE MOBILE MANIPULATOR SYSTEM

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APPENDIX A
TABLES

Table A-1
SURVEY OF ALTERNATE PAINT REMOVAL TECHNOLOGIES

	Non-HAP's Chemical	Methylene Chloride Chemical	PMB	Wheat Starch	Flashlamp/CO_2	Medium-Pressure Water Stripping
No. of Laborers	6 per aircraft	6 per aircraft	1 per nozzle	8 per 8 nozzles	2 per head	8 nozzles, 1/nozzle
Potential Substrate Damage	Composite resin removal	Composite resin removal	Composite resin removal; fiber breakage	Composite pitting	Composite resin removal; temperature rise	Composite resin removal; fiber breakage
Initial Cost	N/A	N/A	$800,000	$4.75 million	$2.6 million	$60,000/nozzle
Maintenance Cost	$17,000/yr	$17,000/yr	$50,000/yr		$32,500/yr	$30,000 + /yr
Safety Requirements	Ventilation	Ventilation, full breathing apparatus and skin protection	Full breathing apparatus, hearing protection	Full breathing apparatus, ventilation, hearing protection	UV protection, hearing protection	Face shield, hearing protection
Safety Hazards	Vapors/liquid contact	Toxic chemical suspect carcinogen	Cd, Pb, Cr dust	Dust	Carbon dioxide, noise, UV	Noise, high psi water
Raw Materials	$15/gal, 300 gal	$7/gal, 350 gal/ aircraft	$2/lb lease type V	$1.35/lb (100,000 lb)	$.05/lb CO_2	$.40/lb
Waste Amount	10,000 gal P-3 aircraft	15,000 gal P-3 aircraft	800 lb fighter size aircraft	8%/cycle	12 lb/helicopter	22,700 gal H_2O 3,500 lb solid
Preparation	32 man-hours	32 man-hours	10 hr	1 1/2 days	2 hr	4 hr
Strip Rate (sq. ft/min)	5-8, >70°F	20	1 to 2	0.3 to 0.9	2.0 to 4.0	1.5
Post Strip	45 min	1.5 hr	20 hr	8 hr	1/2 hr	1 hr
Throughput Time	6 days	4 days	5 days	5 days – 2 shifts	2 to 4 days	5 to 7 days
Process Limits	Metals only	Metals only	No honeycomb, kevlar, or fiberglass		Supplemental process required	Metals only
Cost (sq. ft)	$4.70	$4.30	$4.25		$3.71	$5.20
Aircraft Surface Area (sq. ft)	8,000	8,000	2,200	10,000	Helicopter, 800	17,460

Table A-2
NAVY DEPAINT COST COMPARISON USING AIR FORCE COST COMPARISON MODEL
(Revised May 1998)

© 1998 Aircraft	U.S Air Force Depaint Cost Comparison Model v2.0	Strip Rate sq. ft/min/ Nozzle	Overall Summary Flow Time Days Computed	Implement Cost Ventilation Cost Computed	Implement Cost Implementation Cost Computed	Life Cycle Cost per Square Foot
	(Methylene Chloride Chemical)					
F/A-18	$2,200	N/A	7.1	$5,500,000	$5,506,000	$19.33
P-3	8,000	N/A	5.6	5,500,000	5,515,000	8.37
C-141B	17,400	N/A	6.4	5,500,000	5,521,000	5.08
	(PMB)					
F/A-18	2,200	1.00	3.7	220,000	760,000	9.28
P-3	8,000	1.50	4.4	800,000	3,240,000	7.21
C-141B	17,400	1.50	4.6	1,742,400	7,262,800	5.90
	(Robotic PMB)					
F/A-18	2,200	1.00	3.4	220,000	2,260,000	8.33
P-3	8,000	1.50	4.2	800,000	6,830,000	7.32
C-141B	17,400	1.50	4.4	1,742,400	16,942,800	6.36
	(Mobile Manipulator Flashjet®)					
F/A-18	2,200	1.50	1.6	0	3,706,000	5.64
P-3	8,000	3.00	2.3	0	3,706,000	3.36
C-141B	17,400	3.00	2.9	0	5,484,000	2.25
	(Robotic Flashjet®)					
F/A-18	2,200	1.50	2.2	0	3,268,000	5.24
P-3	8,000	3.00	2.2	0	8,386,000	5.18
C-141B	17,400	3.00	3.6	0	8,386,000	2.79

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APPENDIX B
GLOSSARY

ACGIH	American Conference of Government and Industrial Hygienists
AFB	Air Force Base
CFM	Cubic Feet per Minute
CNO	Chief of Naval Operations
CO_2	Carbon Dioxide
CTC	Concurrent Technologies Corporation
EPA	Environmental Protection Agency
GSA	General Services Administration
HAP	Hazardous Air Pollutant
HEPA	High Efficiency Particulate Air
MAS	Manipulator Arm System
MDA	McDonnell Douglas Aerospace
MERC	Mercer Engineering Research Center
MPW	Medium-Pressure Water
NESHAP	National Emission Standards for Hazardous Air Pollutants
NMP	N-Methyl Pyrrolidone
OSHA	Occupational Safety and Health Administration
PC	Personal Computer
PMB	Plastic Media Blasting
PRAM	Producibility, Reliability, Availability, and Maintainability
PSIG	Pounds per Square Inch Gage
RCRA	Resource Conservation and Recovery Act
SERDP	Strategic Environmental Research and Development Program
TRI	Toxic Release Inventory
WR-ALC	Warner Robins Air Logistics Center

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